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# Computational models for electromagnetic transients in ITER vacuum vessel, cryostat and thermal shield

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ABSTRACT

A set of detailed computational models are reviewed that covers integrally the system "vacuum vessel (VV), cryostat, and thermal shields (TS)" to study transient electromagnetics (EMs) in the ITER machine. The models have been developed in the course of activities requested and supervised by the ITER Organization. EM analysis is enabled for all ITER operational scenarios. The input data are derived from results of DINA code simulations. The external EM fields are modeled accurate to the input data description. The known magnetic shell approach can be effectively applied to simulate thin-walled structures of the ITER machine. Using an integral–differential formulation, a single unknown is determined within the shells in terms of the vector electric potential taken only at the nodes of a finite-element (FE) mesh of the conducting structures. As a result, the FE mesh encompasses only the system "VV + Cryostat + TS". The 3D model requires much higher computational resources as compared to a shell model based on the equivalent approximation. The shell models have been developed for all principal conducting structures in the system "VV + Cryostat + TS" including regular ports and neutral beam ports. The structures are described in details in accordance with the latest design. The models have also been applied for simulations of EM transients in components of diagnostic systems and cryopumps and estimation of the 3D effects of the ITER structures on the plasma performance. The developed models have been elaborated and applied for the last 15 years to support the ITER design activities. The finalization of the ITER VV design enables this set of models to be considered ready to use in plasma-physics computations and the development of ITER simulators.



## 1. Introduction

The Vacuum Vessel, Cryostat, and Thermal Shield are known to have strong electromagnetic impact on each other and surrounding structures. The functions and arrangements of these components are described in detail in [1–4], below a brief quote is extracted to characterize the models developed.

The VV is located inside the magnet system within the TS. It is a large double wall a torus-shaped conducting structure that surrounds the plasma. It features a band of ports used for different functions. The VV has upper, equatorial, and lower port structures.

Normally, a VV port consists of a port extension, and a port stub (that is integral to the main vessel), and a stub extension. The port extensions are equipped with the connecting ducts extended to the cryostat. The vessel consists of the inner and outer shells (both are of 60 mm thick), ribs, shield structures, splice plates, shielding structures for field joints, and mechanical structures on the inner and outer shells to support in-vessel components and to support the vessel weight. The shells of the main vessel are made from SS 316L(N)-IG with stiffening ribs (mainly 40 mm plate) between the shells. The VV is divided toroidally into 9 sectors. Each sector, spanning 40°, includes a set of full port stubs and stub extensions at the toroidal center of the sector and a set of half port stubs. A sector has a cylindrical shape on the straight section of the inboard area that transits to a double curved shape at the inboard vessel top/bottom. Equatorial segment of VV inner shell outboard part of vacuum vessel has a toroidal shape, while the one of VV outer shell has a facet shape. The equatorial ports include regular ports and neutral beam (NB) ports. The regular ports have a rectangular cross-section and are positioned horizontally. The NB ports are located in three adjacent sectors of the machine. The NB port structure and position are different from those of the regular ports. The triangular support structure is located in the lower outboard region. The blanket and divertor are mounted on the vessel interior and all loads are transferred to the vessel.

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The TS is always physically isolated from the VV [3]. TS is composed of a torus and port shaped shield as well as a cylindrical shaped shield with associated openings for penetrations. It is a single wall conducting structure primarily fabricated with 304L stainless steel. The TS is arranged in the primary sub-assemblies: upper cryostat thermal shield, lower cryostat thermal shield, support thermal shield, equatorial thermal shield consists of 2 distinctly different sub components–vacuum vessel thermal shield, equatorial cryostat thermal shield, thermal shield manifold. The panel material is 10–20 mm thick for the CTS and 20 mm for the VVTS with local increases for the joining flanges. All shielding components consist of stainless steel panels with permanently attached circular tubes that are cooled by pressurized helium gas with an 80 K inlet temperature during normal operation. The TS manifolds distribute the helium onto each TS panel. The helium is returned onto the cryoplant. The TS manifolds are located inside of the cryostat. 18 inlet/outlet circuits make up the TS manifold.

The ITER cryostat includes the following main components – as seen from top to bottom: the top lid, which includes a substantial reinforcement structure in the form of trusswork; the main shell (split in two, roughly equal weight sections for installation); the cryostat base; a series of 18 pillars that are bolted to the building floor and to the horizontal section thereby supporting the weight of the vacuum vessel and associated components. The cryostat main shell consists of two cylindrical sections with circumferential stiffening ribs. The cryostat base is formed by three annular flat plate structures. The first is the outer portion from the lower cylinder to the cylindrical stiffening rib. The second is the inner portion from the cylindrical stiffening rib to the lower head support rib. The plate of the outer and the inner portions is 50 mm thick and stiffened with T-sections spaced radially every 10°. The last is a central plate with cylinder. The design has been performed with a wall thickness of the upper and lower cylinders of 50 mm. All of these cylindrical portions are stiffened by longitudinally equally spaced circumferential stiffening rings of T-sections. A total of 18 similar but vertically oriented ribs located on the exterior of the shell between ports. The intermediate horizontal ring is rigidly connected into the building structures. The thickness of the ring is 105 mm. It is connected to the gravity support ring pedestal at its inside and to the upper cylinder at its outside. The upper head is a circular flat plate, normally 40 mm thick, with radial stiffening ribs spaced every 10°.

From this description, VV, Cryostat, and TS can be classified as thin-walled structures that allow the method of magnetic shells [5–8] to be applied for modeling their electromagnetic behavior. The use of this method is most effective if a complex 3D configuration of multiply connected conducting shells is to be modeled. The presentation reflects our experience in simulations of eddy currents, fields and EM loads in VV, Cryostat и TS caused by transient electromagnetics [9]. Since the ITER VV design is finalized [1], the finite-element meshes are put into the final form, and a set of detailed models has been developed for the system “VV + Cryostat + TS”. The models correspond to the latest design options and provide desired computational accuracy under full spectra of EM loads (during normal plasma operating conditions, scenarios of plasma disruption and magnet system discharge).

## 2. Computational models

Modeling with magnetic shells is expanded in [7,8]. A single unknown was determined within the shells in terms of the vector electric potential [5–8] taken at the nodes of a finite-element mesh over a shell. The magnetic shells coincided with surfaces of the conducting structures in almost all models. The computations were performed with the use of the code TYPHOON [8].

Symmetry approximations (periodicity, mirror symmetry/antisymmetry) are implemented in the models via relevant boundary conditions. For each type of symmetry a minimal angular sector is detected (typically, 10–20°), and its local response is superimposed to simulate the EM behavior for a larger sector of 20°, 40°, 180°, or 360°. This enables fine meshing at a reduced computational intensity.

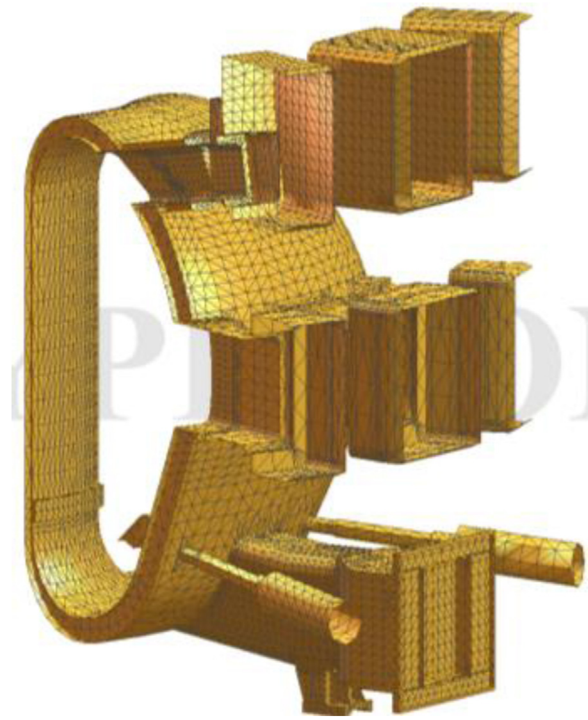

**Fig. 1.** 40° regular VV sector.

VV features a band of ports arranged as 15 regular ports and 3 neutral beam ports, namely two heating ports and one diagnostic port. Modeling of these ports was of special concern.

A consideration is enabled for the contacts between the components designed as well as associated with possible insulation failure. The available set of the shell models is well supportive for flexible and time-effective development of large-scale models. Figs. 1–3 illustrate the FE meshes.

A 40° regular sector of the system “VV + Cryostat + TS” is meshed with 120,000 triangular finite elements. This gives about 60,000 equations to be solved in terms of nodal unknowns. A 3D FE model based on an equivalent approximation, for example, in ANSYS computations, implies much higher dimensionality due to the necessity of (i) filling the intershell space of the structures, (ii) boundary conditions “on infinity”, (iii) nodes with several unknowns. The dimension of such representation is estimated as infimum (N DOF) $\approx 4 \times 10^7$ or higher.

Fig. 4 presents two models developed for the EM study of the TS manifolds over the 360° volume. The external field is simulated at all reference points using the model for a 40° regular sector of the system “VV + Cryostat + TS”. The mutual electromagnetic impact of the components in the system is determined using superposition of individual fields. The thickness of the manifold walls is 2.9 mm. Two design options for the TS manifolds have been studied: with and without electric breaks. For the first option (Option 1) equatorial and support TS were assumed to have electrical breaks on the outlet manifolds, while upper/lower cryostat TS have no electrical breaks there. For the second option (Option 2) TS sub-assemblies were assumed to have no electrical breaks on the outlet manifolds. Two scenarios of plasma disruption have been simulated: Slow Downward Vertical Displacement Event (SD VDE) and Major Disruption (MD36ms) with linear current quench decay. Maximal EM loads are